INTERACTION OF IO'S IONOSPHERE WITH THE JOVIAN MAGNETIC FIELD: IS THIS A REASON OF DEPRESSION IN THE BACKGROUND MAGNETIC FIELD RECORDED BY GALILEO?

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Abstract

Recent observations by the Galileo spacecraft exhibit a large depression in the background magnetic field at Io's wake. The field decrease is nearly 40% of the Jovian background field. Two hypotheses have been put forward to explain the observations: Io possesses an internal magnetic field [Frank et al., 1996] and the field depression is caused by current generated by Io's interaction with its torus [Kivelson et al., 1996a]. Modeling of the Io–plasma interaction contribution performed in Kivelson et al. [1996b] shows that the plasma effects can account for only a part of the observed depression. In this report we show that there is a plasma effect due to the interaction between Io's ionosphere and the Jovian magnetic field which was not taken into consideration in Kivelson et al. [1996b] and which can essentially reduce the background magnetic field at Io's plasma wake.

1 Introduction

One of the interesting findings of the Galileo Orbiter during its encounter (the closest approach altitude was about 900 km) with the Io satellite was the magnetic field depression in the Io downstream wake. At the closest approach, the magnetometer recorded a decrease of about 500 nT relative to the unperturbed Jovian field (in this region the models give about 1800 nT for the planetary magnetic field) [Kivelson et al., 1996a,b; and Frank et al., 1996]. Figure 1 (Figure 1b is from Kivelson et al. [1996b]) shows a schematic view of Galileo's trajectory and the magnetometer recording near Io. Kivelson

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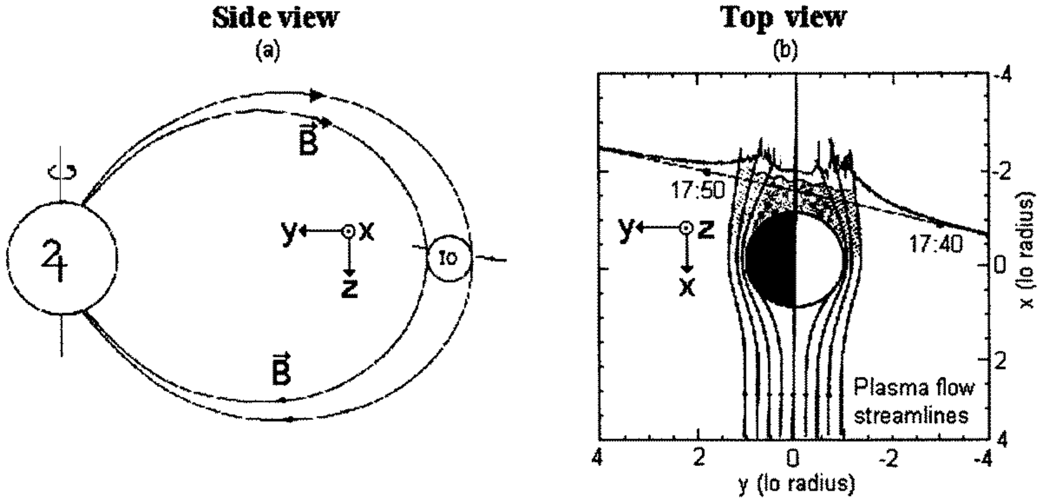

Figure 1: Schematic view of the Galileo trajectory.

et al. [1996a] interpret the observed perturbation of the magnetic field as an evidence that Io has its own magnetic field. Based on the Vojager's plasma measurements and a model of thin Io's ionosphere they show that the electric current flowing in Io's plasma environment and created due to the plasma interaction of Io with the Jovian magnetosphere can provide the magnetic perturbation of only about 250 nT in strength. On the other hand Frank et al. [1996] mark that their plasma measurements of the Io plasma torus mass are about two times greater than used by Kivelson et al. [1996a] and, in addition, the thick ionosphere is observed. These together can provide about 500 nT in strength for the magnetic perturbation due the plasma interaction. Thus, they conclude that the electric current flowing in Io's plasma environment is able to produce the recorded magnetic field perturbation and there is no convincing evidence that Io is endowed with a magnetic moment. In order to explain the observed magnetic perturbation the electric current has to flow from the Jupiter–facing side of Io to the side facing away from the planet and the current value must be about 5×10^6 A. This current value approximately corresponds to the maximum value of the electric current which can be created due to the Io–Jovian magnetosphere interaction with the observed plasma parameters. It should be noted here that the conductance of Io's plasma environment is a tensor with three different components. In general, three types of current (Pedersen, Hall, and field–aligned currents) flowing in different directions are created due to the plasma interaction in a media with such conductance. In the case of Io's plasma environment only the Pedersen currents can produce the observed magnetic field perturbation. Therefore, it seems to be important to consider conditions under which the Pedersen current is the dominant current in the vicinity of Io. As a first step to solve this problem in the next section we investigate a distribution of the electric current created in the partially ionized plasma slab moving through a prescribed magnetic field.

2 Currents in the partially ionized plasma slab moving through a prescribed magnetic field

To investigate the current structure in the partially ionized gas slab consisting of three species: electrons (e), ions (i), neutrals (n) moving through a prescribed magnetic field we use the generalized Ohm's law

$$\vec{E} + \frac{1}{c}[\vec{V} \times \vec{B}] =$$
$$\frac{m_{\mathrm{e}}(\nu_{\mathrm{ei}} + \nu_{\mathrm{en}})}{e^2 n}\vec{j} + \frac{[\vec{j} \times \vec{B}]}{enc} + \frac{F[(n_{\mathrm{n}} m_{\mathrm{n}}\vec{g} - \nabla p_{\mathrm{n}}) \times \vec{B}]}{cnm_{\mathrm{i}}\nu_{\mathrm{in}}} - \frac{\nabla p_{\mathrm{e}}}{en} - \frac{F^2}{cnm_{\mathrm{i}}\nu_{\mathrm{in}}}\rho[\frac{\mathrm{d}\vec{V}}{\mathrm{d}t} \times \vec{B}], \quad (1)$$

$$\rho\frac{\mathrm{d}\vec{V}}{\mathrm{d}t} = \frac{1}{c}[\vec{j} \times \vec{B}] - \nabla p_{\mathrm{e}} - \nabla p_{\mathrm{i}} - \nabla p_{\mathrm{n}} + n_{\mathrm{n}} m_{\mathrm{n}}\vec{g} \quad (2)$$

where $\vec{V}$ is the bulk velocity of the gas, $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields, n_α, m_α, and p_α are the density, mass, and the kinetic pressure of the gas species α, $\alpha = e, i, n$; $\nu_{\alpha\beta}$ is the mean collision frequency of particles α and β, e is the charge of an electron, c is the velocity of light, and $\vec{g}$ is the gravity. In equations (1) and (2) $F = n_{\mathrm{n}} m_{\mathrm{n}}/(n_{\mathrm{e}} m_{\mathrm{e}} + n_{\mathrm{i}} m_{\mathrm{i}} + n_{\mathrm{n}} m_{\mathrm{n}})$ is the relative density of neutrals, $\rho = n_{\mathrm{e}} m_{\mathrm{e}} + n_{\mathrm{i}} m_{\mathrm{i}} + n_{\mathrm{n}} m_{\mathrm{n}}$, and $n_{\mathrm{e}} \simeq n_{\mathrm{i}} \simeq n$. To obtain the expressions describing the electric current distribution we use, also, the mass conservation law

$$\frac{\partial\rho}{\partial t} + \nabla(\rho\vec{V}) = 0, \quad (3)$$

the Maxwell's equations, and the state equations

$$p_\alpha = n_\alpha \kappa T_\alpha \quad (4)$$

where T_α is the kinetic temperature of the gas species α, and κ is Boltzmann's constant.

Let us consider a 2D slab of weak ionized $(1 - F \ll 1)$ gas which moves perpendicular to the prescribed magnetic field $\vec{B_0}$ with the constant velocity $\vec{V}$ (Figure 2). In this case we can assume in (2) $\rho_{\mathrm{e}} + \rho_{\mathrm{i}} + \rho_{\mathrm{n}} \simeq \rho_{\mathrm{n}}$, $\nabla p_{\mathrm{e}} + \nabla p_{\mathrm{i}} + \nabla p_{\mathrm{n}} \simeq \nabla p_{\mathrm{n}}$ and $\mathrm{d}\vec{V}/\mathrm{d}t = 0$ and express the neutral pressure term in (1) via the Ampére force

$$\nabla p_{\mathrm{n}} + n_{\mathrm{n}} m_{\mathrm{n}}\vec{g} \simeq \frac{1}{c}[\vec{j} \times \vec{B}] \quad (5)$$

As a result we come to following form of the Ohm's law

$$\vec{E} + \frac{1}{c}[\vec{V} \times \vec{B}] \simeq \frac{m_{\mathrm{e}}(\nu_{\mathrm{ei}} + \nu_{\mathrm{en}})}{e^2 n}\vec{j} + \frac{[\vec{j} \times \vec{B}]}{enc} - \frac{F}{c^2 nm_{\mathrm{i}}\nu_{\mathrm{in}}}[[\vec{j} \times \vec{B}] \times \vec{B}], \quad (6)$$

We perform our consideration in a Cartesian reference system with the z–axis along the magnetic field $\vec{B_0}$, the x–axis directed along the velocity $\vec{V}$, and the y–axis along the slab (Figure 2). Let us consider a simple case where all parameters depend on the only coordinate x, i.e. $\partial/\partial y = \partial/\partial z = 0$. In this case, taking into account that $\partial B/\partial t = 0$ in

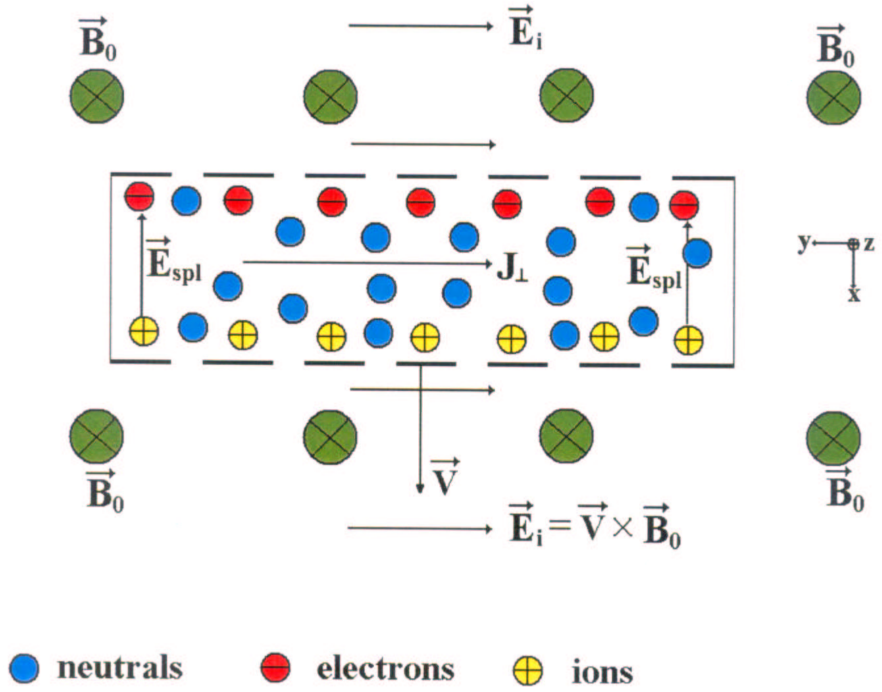

Figure 2: Two–dimension slab of partially ionized plasma moving across a homogeneous magnetic field.

the frame of reference attached to the gas slab, from (6) and Maxwell's equations we get for the components of the electric field

$$\begin{aligned} E_{\rm x} &\simeq \frac{j_y B_0}{enc}, \\ E_{\rm y} &= E_{\rm ind} + \frac{j_y}{\sigma}(1 + \omega_{\rm Be}\tau_{\rm en}\omega_{\rm Bi}\tau_{\rm in}) = 0, \\ E_{\rm z} &= 0, \end{aligned} \tag{7}$$

and of the electric current

$$\begin{aligned} j_{\rm x} &= j_{\rm z} = 0, \\ j_{\rm y} &= -\frac{\sigma}{(1 + \omega_{\rm Be}\tau_{\rm en}\omega_{\rm Bi}\tau_{\rm in})} E_{\rm ind}, \end{aligned} \tag{8}$$

where $E_{\rm ind} = (1/c)VB_0$ is the induced electric field which is created within the gas slab due to its motion through the magnetic field, $\sigma = e^2 n/m_{\rm e}(\nu_{\rm en} + \nu_{\rm ei})$ is the electrical conductivity of a three component gas in the absence of a magnetic field, $\omega_{\rm Be}$ and $\omega_{\rm Bi}$ are the electron and ion gyrofrequencies, respectively, $\tau_{\rm en} = 1/(\nu_{\rm en} + \nu_{\rm ei})$ and $\tau_{\rm in} = 1/\nu_{\rm in}$ are the mean time of electrons and ions free motion, respectively. For the sake of simplicity we restrict ourselves in (8) to the case when the magnetic field $B_{\rm j}$ created by the electric current j is much less than the prescribed magnetic field B_0, i.e. $B = B_0 + B_{\rm j} \approx B_0$. In the Io's plasma environment the electric currents flow in a region where

$$\begin{aligned} &\omega_{\rm Be}\tau_{\rm en} \gg 1, \\ &\omega_{\rm Bi}\tau_{\rm in} \sim 1. \end{aligned} \tag{9}$$

Under these conditions the expression for the y–component of the electric current has a simple form

$$j_{\rm y} \simeq -2\sigma_{\rm P}E_{\rm ind}, \tag{10}$$

where $\sigma_{\rm P}$ is the Pedersen conductivity of three–component plasma. From (8) and (10) we conclude that the current flowing across the magnetic field equals approximately twice the Pedersen current created by the induced field in the gas slab while the currents flowing in other directions are absent. The point is that the currents flowing along the y–direction are a superposition of two types of currents, the Pedersen currents ($j_{\rm P}$) created by the induced electric field $E_{\rm ind}$ and the Hall currents ($j_{\rm H}$) created by the charge splitting electric field $E_{\rm spl}$ (Figure 2)

$$j_y = -(j_{\rm P} + j_{\rm H}) = -(\sigma_{\rm P}E_{\rm ind} + \sigma_{\rm H}E_{\rm spl}), \tag{11}$$

where $\sigma_{\rm H}$ is the Hall conductivity of the plasma. The charge splitting results from different velocities of electron and ion diffusion across the magnetic field. The point is that under condition (9) the electrons are magnetized and aspire after the magnetic field while the ions are nonmagnetized and aspire after the neutrals. The motion with different velocities leads to the creation of space charge and the associated charge splitting electric field $E_{\rm spl}$ which balks the electron escaping that are guided by the magnetic field. The electric field reduces the ion diffusion velocity and increases the electron diffusion velocity. As a result in steady state the ion and electron diffusion velocities are equal. This phenomenon is well known as ambipolar diffusion. In our case the ambipolar diffusion of the electrons and ions across the magnetic field takes place with the constant velocity determined by Io. As it follows from (7) under condition (9) the splitting electric field is equal to the Pedersen current, $E_{\rm spl} \simeq E_{\rm ind}$, the Pedersen and Hall conductivities [see e.g. Krall and Trivelpiece, 1973] are also equal, $\sigma_{\rm H} \simeq \sigma_{\rm P}$, and the expression for y–component of the electric current (11) leads to the expression (10).

3 Conclusion

In the previous section we considered the simple case where a 2D slab of weak ionized plasma moves across a prescribed magnetic field. We showed that the electric currents created in the slab due to its motion through the magnetic field flow only in the direction parallel to the induced electric field. The 2D slab of the plasma is a quite rough approximation of Io's ionosphere. However this example shows that there is a possibility for the total Io ionosphere current to flow in the direction required by the magnetic observations and to provide the observed magnetic perturbation in the absence of an own magnetic field of Io.

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